Centimeter searches for molecular line emission from high-redshift galaxies

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ABSTRACT

We consider the capabilities for detecting low order CO emission lines from high-redshift (z) galaxies using the next generation of radio telescopes operating at 22 and 43 GHz. Low order CO emission studies provide critical insight into the nature of high redshift galaxies, including: (i) determining molecular gas masses, (ii) study of large scale structure through 3-dimensional redshift surveys over cosmologically relevant volumes, (iii) imaging gas kinematics on kpc-scales, and, in conjunction with observations of higher order transitions using future millimeter telescopes, (iv) constraining the excitation conditions of the gas. Particular attention is paid to the impact on such studies of the high frequency limit for future centimeter telescopes. We employ models for the evolution of dusty star forming galaxies based on source counts at (sub)millimeter (mm) wavelengths, and on the observed mm through infrared (IR) backgrounds, to predict the expected detection rate of low-order CO(2-1) and CO(1-0) line emitting galaxies for optimal centimeter(cm)-wave surveys using future radio telescopes, such as the Square Kilometer Array (SKA) and the Expanded Very Large Array (EVLA). We then compare these results to surveys that can be done with the next-generation mm-wave telescope, the Atacama Large Millimeter Array (ALMA). Operating at 22 GHz the SKA will be competitive with the ALMA in terms of the detection rate of lines from high-z galaxies, and will be potentially superior by an order of magnitude if extended to 43 GHz. Perhaps more importantly, cm-wave telescopes are sensitive to lower excitation gas in higher redshift galaxies, and so provide a complementary view of conditions in high redshift galaxies to mm-wave surveys. We have also included in our models emission from HCN. The number of HCN(1-0) detections will be about 5% of the CO detections in the (CO-optimized) 22 GHz surveys, and about

1.5% for 43 GHz surveys. In order not to over-resolve the sources, brightness temperature limitations require that a future large area cm telescopes have much of its collecting area on baselines shorter than 10 km.

Subject headings: Cosmology: observations — Molecules: galaxies — infrared: galaxies — Galaxies: starburst, evolution

1. Introduction

Observations of CO line emission from high redshift (z) galaxies has become an important diagnostic tool in the study of galaxy formation. Such studies include observations of IR-luminous starburst galaxies selected at IR and (sub)mm wavelengths (Brown & van den Bout 1992; Solomon, Downes & Radford 1992; Frayer et al. 1998; Ivison et al. 2001), and active galaxies (QSOs and radio galaxies) selected at optical wavelengths (Omont et al. 1996a,b, 2001; Ohta et al. 1996; Barvainis et al. 1998; Guilloteau et al. 1997, 1999; Papadopoulos et al. 2000, 2001; Carilli, Menten & Yun 1999; Carilli et al. 2002). Due to the sensitivity limitations of current mm-wave telescopes, such studies have been limited to extreme high mass, high luminosity galaxies, corresponding to galaxies with far-IR (FIR) luminosities: $L_{\rm FIR} \geq 10^{12}$ L$_\odot$, and molecular gas masses: M(H$_2$) $\geq 10^{10}$ M$_\odot$. While such systems are rare in the nearby universe, 10^{-6} Mpc^{-3}, or 10^4 times lower than L_* galaxies, (sub)mm surveys suggest that the comoving number density of such objects increases by up to three orders of magnitude by $z \sim 2$ to 3 (Smail, Ivison & Blain 1997; Blain et al. 1999; Barger et al. 1998). Another serious limitation to current instruments is the narrow bandwidth of the spectrometers. Current spectrometers have maximum bandwidths of 0.5 to 1 GHz, corresponding to 1500 to 3000 km s^{-1} at 100 GHz. The limited sensitivity and bandwidth of existing instruments effectively preclude large-volume searches for high-z galaxies via their molecular line emission.

The next generation of mm- and cm-wave telescopes will have sensitivities and bandwidths at least an order of magnitude better than existing instruments. With such capabilities it becomes feasible to consider searches for high-z galaxies at mm and cm wavelengths. This problem has already been addressed in detail for (sub)mm-wave observations using the Atacama Large Millimeter Array (ALMA), the next-generation mm-wave telescope (Blain et al. 2000 – Paper I; Blain 1996, 2001; van der Werf & Israel

1996; Silk & Spaans 1997; Combes, Maoli, & Omont 1999; Gnedin, Silk & Spaans 2001).

This paper dramatically expands the discussion in Paper I of the capabilities of future telescopes to study the evolution of dusty star forming galaxies via their low-excitation molecular line emission. In Paper I, formalism was developed to investigate optimal molecular line surveys which maximize the detection rate of galaxies for a given amount of observing time, and the analysis presented herein relies on the same formalism. The importance of such surveys is delineated in detail in Paper I. To summarize, measuring molecular lines, and especially the low-excitation lines that trace the bulk of gas in the interstellar medium (ISM), provides a direct probe of the massive gas reservoirs required to fuel star formation in nascent galaxies. In addition, the velocity width of the lines provides an estimate of the dynamical mass of the systems. Observations of the infrared background, and source counts at (sub)mm wavelengths, suggest that a substantial fraction of the star formation that occurs in the universe is invisible at optical wavelengths due to dust obscuration (Blain et al. 1999). Future molecular line surveys may be the only way of obtaining a complete census of the redshift distribution of this cosmic star formation.

Paper I emphasized the capabilities of future mm-wave telescopes, such as the ALMA, for discovering high redshift galaxies via their CO emission. The focus of the analysis presented herein is on future cm-wave telescopes, such as the Square Kilometer Array (SKA) and the Expanded Very Large Array (EVLA), for observing low-excitation CO molecular line emission from high-z galaxies. The important difference between mm- and cm-wave observations is that mm-wave telescopes are limited to studying higher order CO transitions from high-z galaxies – CO(3-2) or higher at 100 GHz for $z > 2$ – while cm-wave telescopes probe the lower order transitions, CO(2-1) and CO(1-0). Clearly such complementarity is critical for determining excitation conditions in high-z molecular gas clouds. In particular, mm-wave surveys of high order transitions will be biased toward

high-density, high-temperature gas, with $n(\mathrm{H}_2) > 10^3\,\mathrm{cm}^{-3}$ and $T > 30\,\mathrm{K}$ (Papadopoulos et al. 2001; Papadopoulos & Ivison 2001).

An important advantage of cm-wave surveys is the large fractional bandwidth and primary beam area. At high redshifts cm-wave spectroscopy will be able to map out the 3-dimensional spatial structure of line-emitting galaxies, and thus to trace directly the build up of large-scale structure in the Universe. Both the thickness in redshift, and the projected area on the sky of the surveyed volume, will be much greater in the cm waveband than at mm wavelengths. It is also likely that low-excitation lines will map out a larger fraction of the volume of the ISM in these galaxies, and thus provide the opportunity to study in detail the spatially resolved kinematic structure of most of the gas in the ISM in high-redshift galaxies, which resides in the cold phase. These observations would provide information about both the evolution of the masses of galaxy disks and the disruption of disks by galaxy interactions at large redshifts. This will allow valuable new tests of understanding of the assembly and formation of galaxies.

We use the latest galaxy evolution models from Paper I, modified to take account of additional data and revised cosmology. While these models represent perhaps the best current estimates of the evolution of dusty star forming galaxies, the observational constraints are such that substantial revisions, especially of the source redshift distribution, are certainly possible. Likewise, the design specifications of the next-generation cm-wave telescopes are still being considered. Hence, this paper is not meant as a definitive and final prediction of the results of future molecular line surveys with cm-wave telescopes, but merely to advocate the possibilities. A particular concrete question we hope to address is: what choices in the design of such telescopes (eg. high frequency limit, maximum baseline) will facilitate the study of molecular line emission from high-z galaxies? We assume $\mathrm{H}_0 =$ 65 km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$

2. Dusty galaxy evolution models

The models we employ for predicting CO source counts are updated from Paper I. These models employ an analytic description of pure luminosity evolution of the low-z *IRAS* 60-μm luminosity function (Saunders et al. 1990). The evolution function has the form,

$$g(z) = (1+z)^{3/2} \mathrm{sech}^2[b \ln(1+z) - c] \cosh^2 c. \tag{1}$$

At very low and very high redshifts the function can be approximated by $g(z) \propto (1+z)^{\gamma}$, with $\gamma \simeq 3/2 + 2b \tanh c$ and $\gamma = 3/2 - 2b$ respectively. With the current cosmology, and taking into account all available far-IR and (sub)-mm background, count and redshift distribution data, the values $b = 2.2 \pm 0.1$ and $c = 1.84 \pm 0.15$ are required, if a typical dust temperature of 37 K is assumed. The fitting procedures and details of the information used are explained in Blain et al. (1999). A plot of this function is shown in Fig. 1 of Blain (2002). The evolution peaks at $z \simeq 1.7$, at which the bolometric luminosity density of infrared-luminous galaxies is about 40 times greater than at $z = 0$.

The strength of the emission from CO lines is calculated as described in Paper I. Excitation conditions, and thus line ratios, are derived from a standard large velocity gradient model (Frayer & Brown 1997) with a kinetic temperature of about 50 K and a density of $10^4\,\mathrm{cm}^{-3}$. This model provides a reasonable description of the CO emission from two well-studied FIR-luminous galaxies at $z \sim 2.5$, and their properties are used to normalize the CO emission line strengths to the evolving bolometric luminosity function of galaxies described above.

3. Telescope parameters

Table 1 lists the assumed parameters for telescope capabilities for the SKA,[1] EVLA,[2] and ALMA.[3] Columns 2 and 3 give the antenna diameter and the instantaneous frequency range covered, respectively. Column 4 gives the effective aperture (total collecting area $\times$ aperture efficiency) divided by the system temperature, and Column 5 gives the Field of View (FoV) of the primary elements at the given frequencies. Column 6 gives the rms sensitivity in 1 hour for a FWHM spectral channel of $300\,\mathrm{km\,s^{-1}}$.

The design for the SKA, including the primary stations for the array, the correlator, and the frequency range covered, is still under investigation. For the analysis below we adopt the United States SKA consortium design concept of a square kilometer of collecting area comprised of small (7m) diameter antennas, arranged in 1000 stations of 26 antennas per station (Cordes, Preston, & Tarter 2001). We assume the elements in each station are closely packed ($\sim$ 1m separation), implying an effective station diameter of about 40m. Beam-forming correlators generate 'effective beams' at each station corresponding roughly to the diffraction limited beam of a 40m diameter antenna. Signals from these effective beams are then cross correlated with the corresponding beams of other stations. The current specifications for the SKA require imaging of the full primary beam of the 7m elements, thereby requiring roughly $(\frac{40}{7})^2 = 33$ beams per station. The number of cross correlations (per polarization and lag channel) required for this type of a system is then the sum of the number of cross correlations between stations $= \frac{1000^2}{2} \times 33 = 1.6 \times 10^7$, plus the number of cross correlations per station (ie. the beam-forming correlator) $= \frac{25^2}{2} \times 1000 \times 33 = 1.0 \times 10^7$,

[1]http://www.skatelescope.org

[2]http://www.aoc.nrao.edu/doc/vla/EVLA

[3]http://www.alma.nrao.edu/info

for a total of 2.6×10^7 cross correlations. This value is an order of magnitude smaller than the 3.4×10^8 cross correlations required in the case of full cross correlation of the 26000 7m elements. The trade-offs between full cross correlation and beam forming instruments are in imaging fidelity, which is not a critical issue for the CO searches discussed herein, and in calibration flexibility, ie. the difficulty and complexity is shifted from the construction of the large correlator required for full cross correlation to ensuring the stability of the many beam-forming correlators. The analysis discussed below is not critically dependent on the specific design of the array stations, except with respect to the imaging FoV. For a fixed collecting area a large FoV is clearly preferable for surveys, as the source detection rate increases linearly with FoV.

An important point is the high-frequency limit of the SKA. The current straw-man design has a maximum frequency of 22 GHz. However, Weinreb & Bagri (2001) have shown that going to higher frequencies may be feasible, both in terms of the antennas and the receivers. In this paper we consider CO line searches in a 43-GHz band in addition to the standard 22-GHz band. One of the main motivations of this paper is to gauge the scientific advantages of going to higher frequency with future large area cm telescopes. Such information is required for proper understanding of the trade-offs between scientific capability and cost. We assume a 4-GHz instantaneous total bandwidth, and a 22-GHz aperture efficiency that is a factor two less than that at 5 GHz, ie. a 'half-SKA'.

The EVLA is included in the analysis since it represents the nearer-term capabilities for cm-wave high-z CO surveys. The EVLA represents a major step forward in the study of low-order high-z molecular lines in a number of ways. First, through improved receivers and antenna structures the EVLA will be about twice as sensitive as the current VLA at 43 GHz for spectral line observations. Second, the current VLA correlator is limited to only a 50-MHz bandwidth with 7 spectral channels, which corresponds to only 350 km s^{-1} at

43 GHz. Such a narrow band both precludes searches for high-z CO emission and provides very limited spectral information (Carilli et al. 1999). The EVLA will have an 8-GHz bandwidth in two polarizations with 16000 spectral channels. Third, the current VLA high-frequency bands are limited to 20.5–25 GHz and 40–49 GHz. The EVLA will have continuous frequency coverage from 1 to 50 GHz.

The ALMA is included as a standard of comparison for future (sub)mm telescopes (see Paper I for details). For both the EVLA and the ALMA we consider the optimum bands for CO searches (40 and 230 GHz, respectively). Note that the sensitivity of the EVLA at 43 GHz is comparable to that expected for ALMA at 43 GHz – the larger collecting area of the EVLA is off-set by the higher aperture efficiency and better observing site for ALMA. The inclusion of a 43 GHz system for ALMA is currently under debate. If such a system is included, then the sensitivity for the EVLA in Table 1 is essentially that expected for the ALMA at this frequency, while the ALMA will have a factor four larger FoV.

Arrays of heterodyne receivers on large single dish telescopes offer a potentially competitive method for performing wide field molecular line surveys. In order to sample the same area of the sky with a single dish relative to an interferometer the number of independent single dish beams that need to be sampled is given by the ratio of the FoV of the interferometer to that of the single dish. For example, the 100-m Green Bank Telescope[4] and the EVLA have similar collecting areas, so a 16 element receiver array on the GBT will survey a similar area of the sky as the EVLA with comparable sensitivity. A similar size receiver array on the 50-m Large Millimeter Telescope (LMT)[5] will sample the same FoV as the ALMA, with about 25% of the sensitivity. Of course, a wide-band autocorrelation spectrometer will be required for each element of the receiver array. The telescope optics in

[4]http://www.gb.nrao.edu/GBT/

[5]http://lmtsun.phast.umass.edu/

both cases (the GBT and the LMT) will support such receiver arrays, since both telescopes have been designed to support large format (30×30) bolometer cameras.

4. Analysis

4.1. Optimal Surveys

As a metric of the capabilities of the different telescopes we use the detection rate for an ‘optimal survey’. The optimal survey balances area surveyed versus sensitivity to sample the source counts at the ‘knee’ of the distribution, corresponding to the regime where $N(>S) \propto S^{-2}$, where S is the flux in the line (see Paper I for details). This criterion maximizes the number of sources detected in a given observing time.

In Fig. 1 we show the predicted 22- and 43-GHz line source counts for a 4-GHz bandwidth using the formalism for infrared-selected galaxy evolution developed in Paper I. The line counts increase approximately linearly with bandwidth. Table 2 lists the frequency ranges and optimal depths for the different telescopes, as well as the number of pointings per hour for the optimal depth and the detection rate of high-z CO-emitting galaxies. For the baseline specification of a 22 GHz high frequency upper limit, the SKA galaxy detection rate will be a factor two larger than that of the ALMA. If the high frequency limit is increased to 43 GHz, then the SKA becomes the pre-eminent instrument for discovering high redshift galaxies via their CO emission, detecting 100’s of galaxies per hour. The EVLA is clearly much slower than the SKA in terms of discovering high redshift galaxies due to its lower sensitivity and smaller FoV.

It is important to keep in mind that the line surveys at different frequencies are sampling different CO transitions at different redshifts. In Fig. 2 we delineate the detection rates in terms of the different transitions and redshifts. Surveys with the SKA at 22 GHz to

the optimal depth of $10^{-23}\,\mathrm{W\,m^{-2}}$ detect almost exclusively the CO(1-0) line from galaxies with $L_{\rm FIR} \geq 1.6 \times 10^{12}\,\mathrm{L_\odot}$ at $z \simeq 4.2$. At 43 GHz at the optimal depth of $10^{-22}\,\mathrm{W\,m^{-2}}$, about 92% of the detections are CO(1-0) lines from galaxies with $L_{\rm FIR} \geq 2 \times 10^{12}\,\mathrm{W\,m^{-2}}$ at $z \simeq 1.7$, with about 7.5% being CO(2-1) lines from galaxies with $L_{\rm FIR} \geq 2.4 \times 10^{12}$ at $z \simeq 4.3$, and perhaps 0.5% of the detections being CO(3-2) emission from galaxies with similar FIR luminosity but at $z \simeq 7.0$, if such galaxies exist.

Surveys with the ALMA at 230 GHz to the optimal depth of $4 \times 10^{-21}\,\mathrm{W\,m^{-2}}$ are dominated by galaxies with $L_{\rm FIR} \geq 4 \times 10^{11}\,\mathrm{L_\odot}$, at $z \sim 1$ to 2, emitting CO(4-3) to CO(6-5), with a minor contribution from galaxies with $L_{\rm FIR} \geq 5 \times 10^{10}\,\mathrm{L_\odot}$ at $z \sim 0.5$ emitting CO(3-2) and from more-luminous galaxies with $L_{\rm FIR} \geq 2.4 \times 10^{12}\,\mathrm{L_\odot}$ emitting CO(7-6) at $z \sim 2.5$. The ALMA can also potentially detect a comparable number of redshifted fine-structure lines from higher redshifts in this band (Paper I).

4.2. Other issues: Brightness temperature, clustering, and HCN contamination

We consider briefly a few issues relating to the cm-wave study of CO emission from high redshift galaxies, including: (i) maximum baselines for the array given the expected brightness temperatures, (ii) the capabilities of studying large scale structure through optimal surveys, and (iii) contamination of such surveys by emission from HCN – the next strongest thermal molecular emission species in the relevant frequency range.

An important issue when considering detecting thermal emission from high redshift galaxies with future cm telescopes is the maximum baselines dictated by the intrinsic brightness temperature of the emission. The expected (rest-frame) brightness temperature for the CO emission from high-z galaxies is likely to be ≤ 40 K. This corresponds to an

observed brightness temperature of ≤ 8 K for a source at $z = 4$. The peak flux density of the line for the optimal 43-GHz survey corresponds to about 0.2 mJy for the SKA. In order not to spatially over-resolve the sources, much of the collecting area of the array must then be on baselines ≤ 10 km, corresponding to $\geq 0.14''$ resolution at 43 GHz.

The second issue is large scale structure. The large number of galaxies discovered over a relatively narrow redshift range for sensitive molecular line surveys at cm wavelengths has the added benefit of facilitating three-dimensional studies of large-scale structure at moderate and high redshifts. Operating at 20–24 GHz, the optimal SKA survey with a station diameter of 7 m detects CO(1-0) emission from about 360 galaxies in 24 hours. These galaxies are in the redshift range $z = 3.79$ to 4.75 over an area of 3.5 deg^2, corresponding to a comoving volume of 0.044 Gpc^3. At the higher frequency of 40-44 GHz, the CO(1-0) emission from about 4200 galaxies would be detected in 24 hours from $z = 1.61$ to 1.88 over an area of 23 deg^2 and a comoving volume of 0.085 Gpc^3.

A volume of about 0.1 Gpc^3 corresponds to a representative volume of the universe, and so these surveys will provide excellent probes of large-scale structure. The geometries of both of these daily survey volumes are only about five times deeper than they are wide. This should ensure that three-dimensional large-scale structure is sampled reliably. The space density of CO-emitting galaxies is expected to be about 100 times lower than for optically-selected, spectroscopically-confirmed Lyman-break galaxies (Steidel et al. 1999), and about 10 times less than submm-selected galaxies (Blain et al. 1999). However, the geometry of the three-dimensional redshift surveys should make low-excitation CO surveys an ideal tracer of large-scale structure. In particular, as the CO line surveys sample higher luminosity galaxies, their clustering strength relative to the dark matter at high redshift might be stronger than for lower luminosity galaxies in standard hierarchical galaxy formation models (Davis et al. 1985). Whether this is true will provide important new

information about bias and the galaxy formation process, especially as mass measurements will be available for comparison from CO line widths and excitation ratios.

Finally there is the issue of HCN emission. Solomon et al. (1997) have shown a non-linear relationship between L'(CO(1-0)) (in K km s^{-1} pc^2) and $L_{\rm FIR}$ for galaxies in the sense that high $L_{\rm FIR}$ galaxies have lower values of L'(CO(1-0)) than would be expected based on a linear relationship. Considering $L_{\rm FIR}$ to be a measure of star formation rate, and L'(CO(1-0)) to be a measure of molecular gas mass, this would imply an increase in star formation efficiency ($\equiv \frac{\rm Star\ Formation\ Rate}{\rm Gas\ Mass}$) with increasing luminosity, in particular for galaxies with $L_{\rm FIR} \geq 10^{11}$ L$_\odot$ (Solomon et al. 1997). For dense nuclear starbursts a number of groups (Solomon et al. 1997; Mao et al. 2000; Weiss et al. 2001) have shown that the densities are such that the entire interstellar medium in the starburst regions may be molecular, and that the CO(1-0) emission may be dominated by this molecular inter-cloud medium, as opposed to being from the denser star forming clouds themselves. In this situation it appears that higher density molecular tracers, such as HCN, which has a critical density of order 10^5 cm^{-3}, may be a better probe of the star forming clouds themselves. Gao & Solomon (2001) show that the relationship between L'(HCN(1-0)) and $L_{\rm FIR}$ remains linear, with $L_{\rm FIR} = 863 \times L'(HCN(1-0))$ over the range: $L_{\rm FIR} = 10^{10}$ L$_\odot$ to 10^{12} L$_\odot$ (see Solomon 2001). Given this linear relationship, and the non-linear relationship between $L_{\rm FIR}$ and L'(CO(1-0)), the ratio: $\frac{L'({\rm HCN}(1-0))}{L'({\rm CO}(1-0))}$ varies from about 0.025 for galaxies with $L_{\rm FIR} = 10^{10}$ L$_\odot$ to 0.10 for $L_{\rm FIR} = 10^{12}$ L$_\odot$.

In order to estimate the contamination of optimal cm-wave CO surveys by HCN emission, we have included the HCN(1-0) (88.6 GHz rest frequency) emission in the galaxy formation models discussed in section 2. At the most efficient depths for the CO searches, we find that the number of HCN(1-0) detections would be about 5% of the total number of CO(1-0) lines at 22 GHz and about 1.5% of the total number of lines at 43 GHz. This

emission would correspond to galaxies with $L_{\rm FIR} \sim 10^{13}$ $L_\odot$ at $z \sim 3$ for the 22 GHz survey, and similar luminosity galaxies at $z \sim 1$ for the 43 GHz survey. Hence, HCN emission should not present a major confusion problem for such optimal cm-wave CO line searches. On the other hand, we also find that the fractional contamination by HCN is likely to increase with the depth of the survey, eg. a 22-GHz survey to a depth of 10^{-24} W m^{-2} will contain about 20% HCN(1-0) lines.

5. Discussion

From Table 1 and Fig. 2, it can been seen that future large area cm-wave telescopes operating at 22 GHz will be competitive with future mm-wave telescopes in terms of discovering high-z star-forming galaxies through their molecular line emission. Increasing the high frequency limit to 43-GHz allows for optimal surveys which are 20 times faster than the ALMA in terms of discovering high-z galaxies.

Detection rates are a simplistic metric for the ALMA and the SKA, and it is important to emphasize their complementarity. ALMA surveys will be dominated by higher-order CO lines from intermediate redshift ($z \sim 1 - 2$), intermediate luminosity ($L_{\rm FIR} \sim$ few $\times 10^{11}$ $L_\odot$) objects. Surveys with the SKA at 22 GHz will be dominated by low-order transitions from higher luminosity ($L_{\rm FIR} \sim 10^{12}$ $L_\odot$) galaxies at higher redshifts ($z \sim 4$).

For the EVLA at 43 GHz the combined small FoV and low sensitivity make it a much slower survey instrument that either the ALMA and SKA. However, the EVLA has adequate sensitivity to resolve and study at sub-arcsec angular resolution the low-order CO emission from individual FIR-luminous, high-z objects selected from wide-field surveys at other wavelengths, such as surveys using (sub)mm bolometer arrays on large single-dish telescopes. And perhaps most importantly, the large fractional bandwidth of the EVLA will

allow for redshift determinations via molecular line searches using pointed observations of individual objects. The EVLA will thus provide the first look into the nature of low-order CO emission from high-z galaxies. The importance of such capabilities has already been demonstrated with the current VLA in a few extreme cases, although the limited bandwidth effectively precludes proper spectroscopy (Papadopoulos et al. 2001; Carilli et al. 1999, 2002).

The CO excitation conditions assumed in the models of section 2 could lead to pessimistic predictions for the low-order transitions because the velocity integrated line flux density increases roughly with the square of the frequency (ie. constant brightness temperature), at least to CO(4-3) (Paper I). While this appears to be roughly appropriate for infra-red selected galaxy samples, our models do not include the possibility of a population of molecular gas-rich, high redshift galaxies with lower excitation conditions. For example, the CO excitation conditions for the Milky Way disk inside the solar radius (excluding the Galactic center) imply roughly equal velocity integrated flux density for CO(1-0) and CO(4-3) (Fixsen, Bennett, & Mather 1999). If such a population of galaxies exists, then the predictions from our models can be considered lower limits to the cm-wave source counts for molecular line surveys. Recent observations with the VLA provide evidence that such a population may indeed exist (Papadopoulos et al. 2001).

Limitations to the intrinsic brightness temperature of the thermal line emission from high redshift galaxies require that much of the collecting area of future large area radio telescopes be concentrated on baselines $\leq$ 10 km. On the other hand, having baselines out to 10 km provides the important capability of imaging the emission on scales relevant to galaxies ($0.14'' \simeq 1$ kpc), and for resolving the multiple images of the order of 1% of line-emitting galaxies expected to be gravitationally lensed by foreground galaxies.

Lastly, we have found that HCN(1-0) emission will not be a major source of confusion

to optimal cm-wave CO line searches, comprising about 5% of the total number of detected galaxies at 22 GHz and 1.5% at 43 GHz. Of course, once identified as such, HCN is interesting in it's own regard as a better tracer than CO of the star forming clouds in active star forming galaxies (Solomon 2001).

Like studies of star formation in our own galaxy, it has become clear that a complete census of the star-formation history of the universe requires an understanding of the contribution from galaxies that are obscured by dust at optical wavelengths. The next generation mm- and cm-wave telescopes will provide unique, and complementary, capabilities for studying the thermal and non-thermal line and continuum emission from such systems at sub-arcsecond spatial resolution.

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REFERENCES

Barger, A.J., Cowie, L.L., Sanders, D.B. et al. 1998, Nature, 394, 248

Barvainis, R., Alloin, D., Guilloteau, S., & Antonucci, R. 1998, ApJ, 492, L13

Blain, A.W., 2002, in *Starburst Galaxies Near and Far*, eds. D. Lutz & L. Tacconi (Springer: Berlin), p. 303

Blain, A.W., 1996, in 'Science with large millimetre arrays' Shaver, P.A. ed., Springer: Berlin, p. 70

Blain, A.W., 2001, in 'Science with ALMA' A., Wootten ed., PASP Vol. 235 in press

Blain, A.W., Frayer, D.T, Bock, J.J, & Scoville, N.Z. 2000, MNRAS, 313, 559 (Paper I)

Blain, A.W., Smail, I., Ivison, R.J., & Kneib, J.P. 1999, MNRAS, 302, 632

Brown, R.L. & van den Bout, P. 1992, ApJ, 397, L19

Burigana, C., Danese, L., De Zotti, G., Franceschini, A., Mazzei, P., & Toffolatti, L. 1998, MNRAS, 287, L17

Carilli, C. L., Menten, K.M. & Yun, M. S. 1999, ApJ, 521, L25

Carilli, C. L., Kohno, K., Kawabe, R. et al. 2002, AJ, in press (astro-ph/0112492)

Combes, F. Maoli, F., & Omont, A. 1999, A&A, 345, 369

Cordes, J., Preston, B., & Tarter, J. 2001, 'A Road Map for the US Development Efforts on the SKA,' http://usska.org/techreports/index.html

Davis, M., Efstathiou, G., Frenk, C.S., & White, S.D.M. ApJ, 292, 371

Fixsen, D.J., Bennett, C.L., & Mather, C. 1999, ApJ, 526, 207

Frayer, D.T. & Brown, R.L., 1997, ApJS, 113, 221

Frayer, D.T., Ivison, R.J., Scoville, N.Z., Yun, M., Evans, A.S., Smail, I., Blain, A.W., Kneib J.-P., 1998, ApJ, 506, L7

Gao, Y. & Solomon, P. 2000, BAAS, 197, 9603

Gnedin, N.Y., Silk, J. & Spaans, M. 2001, MNRAS, in press

Guilloteau, S., Omont,A., McMahon, R.G., Cox,P., & Petitjean,P. 1997, A&A, 328, L1

Guilloteau, S., Omont,A., McMahon, R.G., Cox,P., & Petitjean,P. 1999, A&A, 349, 363

Ivison, R.J., Smail, I., Frayer, D.T., Kneib, J.-P., Blain, A.W., 2001, ApJ, 561, L45

Mao, R.Q., Henkel, C., Schulz, A. et al. 2000, A&A, 358, 433

Ohta, K., Yamada, T., Nakanishi, K., Kohno, K., Akiyama, M., & Kawabe, R. 1996, Nature, 382, 426

Omont, A., Cox, P., Bertoldi, F., McMahon, R.G., Carilli, C.L., & Isaak, K. 2001, A&A, 374, 371

Omont, A., McMahon, R. G., Cox, P., Kreysa, E., Bergeron, J., Pajot, F., & Storrie-Lombardi, L.J. 1996a, A&A, 315, 1

Omont, A., Petitjean, P., Guilloteau, S., McMahon, R. G., Solomon, P. M., & Pecontal, E. 1996b, Nature, 382, 428

Papadopoulos, P.P., Röttgering, H., van der Werf et al. 2000, ApJ, 528, 626

Papadopoulos, P.P., Ivison, R.J., Carilli, C.L., & Lewis, G. 2001, Nature, 409, 58

Papadopoulos, P.P. & Ivison, R.J. 2001, MNRAS, in press

Saunders W., Rowan-Robinson, M., Lawrence, A., Efstathiou, G., Kaiser, N., Elllis, R.S., & Frenk C.S., 1990, MNRAS, 242, 318

Silk, J. & Spaans, M. 1997, ApJ, 488, L79

Smail, I., Ivison, R.J., & Blain, A.W., 1997, ApJ, 490, L5

Steidel, C.C., Adelberger, K.L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1

Solomon, P.M., Downes, D., & Radford, S. 1992, Nature, 356, 318

Solomon, P.M., Downes, D., Radford, S., & Barrett, J.W. 1997, ApJ, 478, 144

Solomon, P.M. 2001, in *Starburst Galaxies Near and Far*, eds. D. Lutz & L. Tacconi (Springer: Berlin), p. 173

van der Werf, P.P. & Israel, F.P., 1996, in ‘Science with Large Millimetre Arrays’ ed. Shaver, P.A., (Springer: Berlin), p.$\dot{5}$1

Weinreb, S. & Bagri, D. 2001, in ‘SKA: Defining the Future’ Tarter J. ed. SETI Science Institute: California

Weiss, A., Neininger, N., Hüttermeister, S., & Klein, U. 2001, A& A, 365, 571

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Table 1: Telescope Parameters

Telescope	Antenna diameter (m)	Frequency (GHz)	$A_{\rm eff}/T_{\rm sys}$ ($\mathrm{m^2\,K^{-1}}$)	FoV ($\mathrm{arcmin^2}$)	1-hr rms[a] (μJy)
SKA	7	20 - 24	5600	40	2.5
SKA	7	40 - 44	4000	10	2.5
EVLA	25	38 - 46	75	0.8	100
ALMA	12	222 - 238	100	0.15	45

[a]rms noise in 1 hour for a 300 km $\mathrm{s^{-1}}$ channel.

Table 2: Detection rates for optimal surveys.

Telescope	Frequency (GHz)	Optimal depth ($\mathrm{W\,m^{-2}}$)	Pointings[a] ($\mathrm{hour^{-1}}$)	Rate[b] ($\mathrm{hour^{-1}}$)
SKA	20 - 24	10^{-23}	13	15
SKA	40 - 44	10^{-22}	346	176
EVLA	38 - 46	10^{-22}	0.22	0.02
ALMA	222 - 238	4×10^{-21}	60	7.5

[a]Number of pointings per hour for the optimal survey.

[b]Number of 5σ line sources detected per hour observing time.

Figure Captions

Figure 1: Cumulative source counts of 300-km-s^{-1} wide CO lines at 22 GHz (solid line) and 43 GHz (dash line), developed from the results of Blain et al. (2000, Paper I). A 4-GHz-wide band is assumed.

Figure 2: The detection rate of high-z CO emission lines for 'optimal surveys' using the ALMA at 230 GHz and the SKA at 22 and 43 GHz. The histograms delineate the contribution from different CO transitions at different redshifts, as listed in each segment of the histogram. Note that the quoted redshifts are the mean values for the band covered.

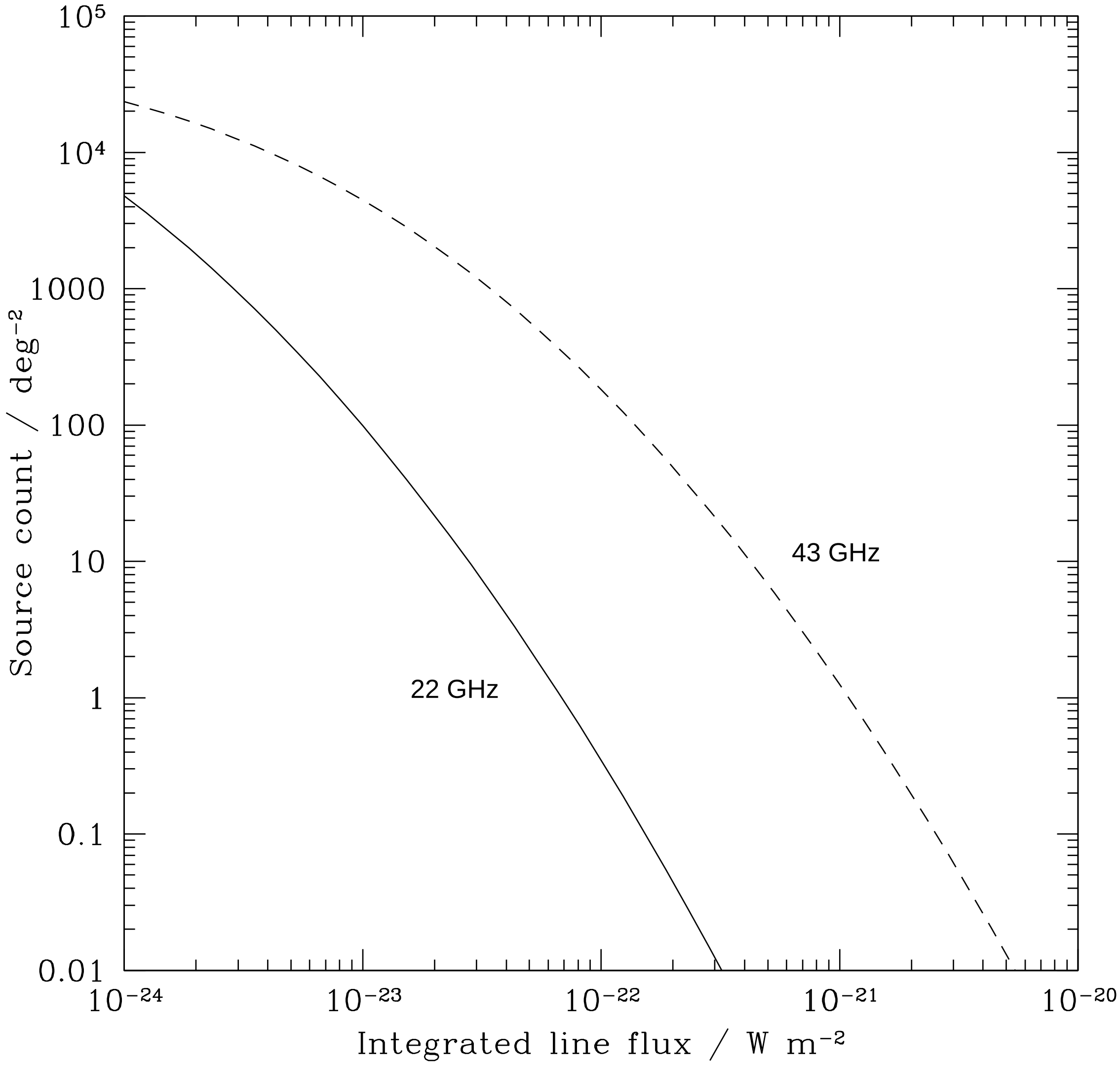
10^5
10^4
1000
100
10
1
0.1
0.01
Source count / deg^-2
43 GHz
22 GHz
10^-24
10^-23
10^-22
10^-21
10^-20
Integrated line flux / W m^-2

Fig. 1.—

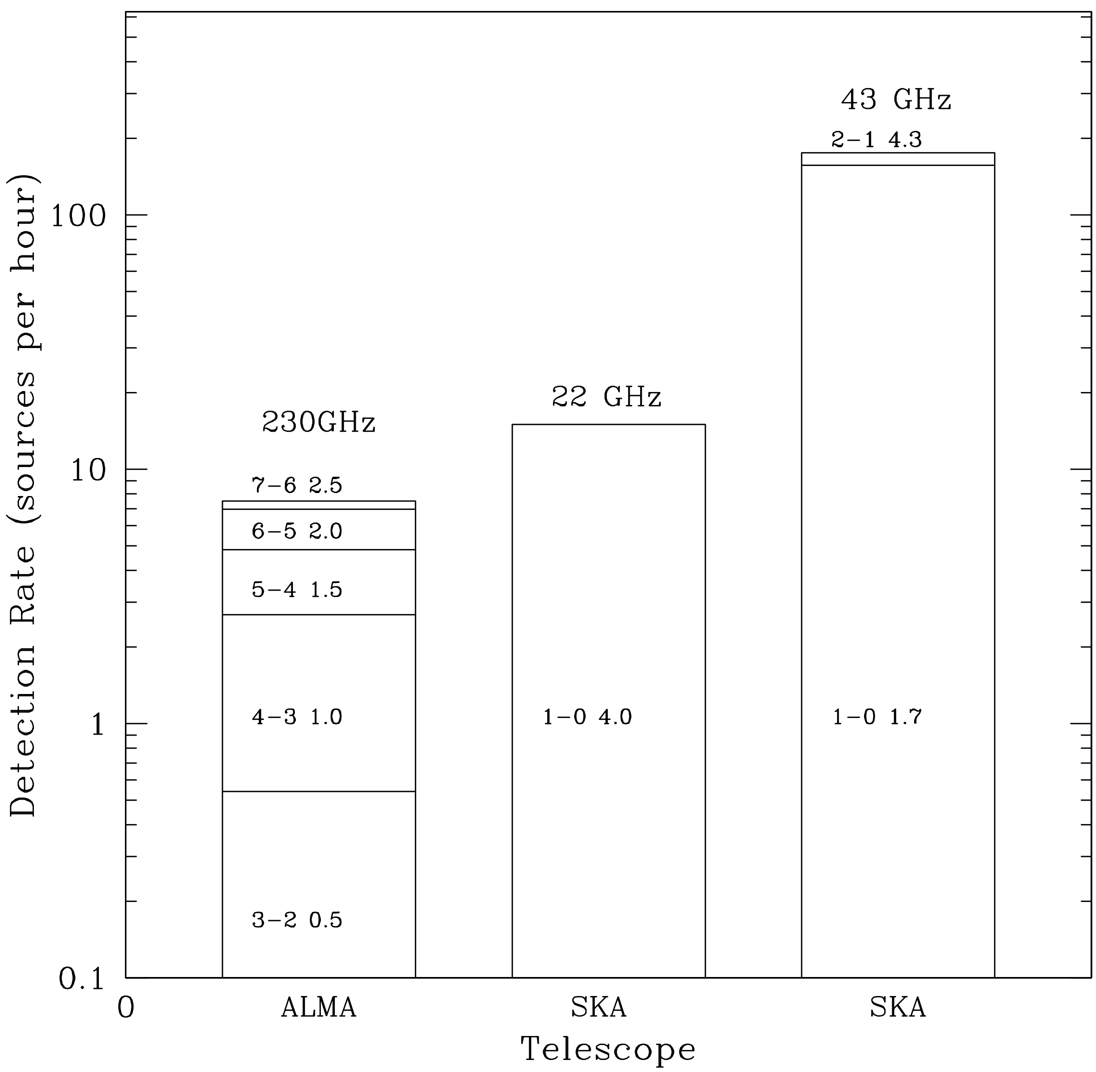
Detection Rate (sources per hour)
100
10
1
0.1
0
230GHz
7−6 2.5
6−5 2.0
5−4 1.5
4−3 1.0
3−2 0.5
22 GHz
1−0 4.0
43 GHz
2−1 4.3
1−0 1.7
ALMA
SKA
SKA
Telescope

Fig. 2.—